Radiometry and Metrology at NSLS-II
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Report on 7/18/07 Breakout Session
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Based on the *brief* breakout session of July 18 (2 hours), the following could be ascertained regarding future possible beamline(s) for radiometry and metrology at NSLS-II.

Agenda Summary

- 25 people attended the session.
- User Survey forms were distributed; 9 completed forms were returned.
- 5 talks were given, see http://www.bnl.gov/nsls2/workshops/UserWorkshop_SBDG.asp
- A brief brainstorming session was held to discuss the beamline features needed to serve the community.
- Participants were told that "hopefully" a "real" (at least 1 full day) workshop on the subject would be held later in the CY to allow more discussion.

The following sections complete this report:

Scientific Scope

Synchrotron Instrumentation.
The needs of modern domestic synchrotron beamlines include both lab-based and at-wavelength characterization of x-ray optics. Proving the performance of beamline optics is a critical component to vendor management and overall scientific success of scientific programs which rely on such high performing beamlines. At-wavelength metrology and characterization is expected to be needed for optics, detectors, and other novel components developed throughout the lifetime of the light source. One can conceive of three basic categories of optics which require at-wavelength metrology: nanofocusing optics (including multilayer Laue and kineform lenses), coherence-preserving optics (including reflective, transmissive and diffractive optics), and beamline optics with less strict requirements on coherence performance but may have other metrics as needed for the scientific application, such as flux, beam uniformity, harmonic purity, etc. In addition, development of various types of detectors is needed for synchrotron beamlines, including radiometric and/or spatial detectors for monitoring the photon beam for the beamline and accelerator, and characterization of large-area detectors for diffraction and imaging.

While development and characterization of some "high-performance" and "standard" beamline optical components are anticipated to be supported by the facility internally, many metrology needs may not be met by this approach. In an effort to support as general a scientific need as possible, this community is currently exploring metrology/radiometry support for beamline components as part of the relevant scientific mission, thereby justifying access via the approved process. In particular, the performance of coherence-preserving reflective and transmissive optics is expected to be a potentially overlooked need which is not explicitly addressed in the existing NSLS-II project plan. Such optics characterization will be relevant for all beamlines. In fact, even as each synchrotron will need its own metrology lab and beamline(s), there is an expected benefit to the entire DOE-BES synchrotron community to apply uniformly the best metrology methods and instrumentation available within the complex.

> Ken Kriesel of PSL has indicated interest in metrology of beamline optics and subsystem performance; e.g. reflectance curve, focal length, energy resolution of PGM; also metrology of machined parts. This is part of development of new beamlines and upgrades of beamlines transitioning from NSLS.
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> Valeriy Yashchuk identified limitations of existing metrology to be able to confirm the performance of high-performance x-ray mirrors, to the 0.1-0.25 urad figure error level. He points out that most capability in this technology lies outside the US, and states "DOE should take national leadership and direct development of the core instrumentation and organize a national center for x-ray metrology and advanced manufacture". Also he reminds us that many existing beamlines are losing 2x-40x of incident beam flux on mirrors and lifetime of the optics scales inversely with brightness; these observations suggest that achieving world's highest brightness at NSLS-II beamlines will not be achievable without significant effort in metrology and vendor management. He also stated that metrology beamlines must be capable of measuring gratings (at wavelength) since optical methods are useless for that.
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> Lahsen Assoufid identified need to reach 0.05 nm repeatability of microinterferometry, with stitching to reach entitlement. He stated that mirrors (and vibration) ultimately limit resolution, for example ~ 90 nm resolution at 15 keV at APS, 70 nm at 13 keV at ESRF using K-B mirrors. At-wavelength characterization with 10 μm pencil beam and CCD detector such as done at ESRF is recommended as it can identify additional slope error not identifiable by optical LTP. He stated that an x-ray grating interferometer useful for at-wavelength sensing and characterization of wavefront. Importantly, Be windows were found to significantly degrade beam coherence (wavefront quality). He identified a need for synchrotron white light for "wide-bandwidth 2D spatial profiling of optics". Quote from Lahsen: "At wavelength x-ray metrology is essential and certainly metrology beamlines are very welcome in this area."

All users recognize the importance of at-wavelength validation of beamline optics, and the need for details like thermal effects in raytracing models.

Inertial Confinement Fusion.
Absolute radiometric calibration of detectors and components is critical to the success of several federal science initiatives. Most prominent at this meeting was the DOE-NNSA contingent (LANL, SNL, LLNL, NSTec, and LLE), which produces inertial confinement fusion (ICF) for a wide range of scientific

programs, including National Ignition Campaign, Plasma Physics, and High Energy Density Physics. Facilities at LLNL (NIF), SNL (Z), and LLE (Omega) provide platforms for science in these programs and each requires regular x-ray calibration of radiometric detectors and other components. Energies presently used are 0.2-6.5 keV, with occasional use at higher energies. International collaborative users include CEA (France), AWE (UK). High-accuracy absolute radiometric calibration of x-ray detectors and components are critical to these programs as they typical comprise bandpass x-ray spectrometers which provide the plasma temperature, a core diagnostic for the ICF platforms themselves. NIF is expected to eventually become a DOE scientific user facility once it is completed. Beyond the core radiometric needs, development efforts of LLNL, LANL, and SNL for ICF instrumentation continue to require flexible sources of x-rays (i.e. synchrotron radiation). Present examples of development efforts include verifying reproducibility of absolute radiometric photocathodes, as well as calibrating grating spectrometers, x-ray film, and other x-ray imaging instrumentation. Currently related metrology/radiometry is occurring at NSLS beamlines U3c and X8a.

> Steve Vernon from LLNL described the x-ray radiometric need of NIF, and Tom Tierney described some of the related work underway and projected for LANL. Currently, laser drive experiments at Omega (at LLE, in Rochester, NY) require semiannual calibration of a single 18-channel (60 component) Dante x-ray spectrometer. This need is expected to more than triple by 2009 as NIF comes online. Regarding Dante, Steve says “This instrument is used to tailor the laser drive and set the conditions we want for ICF so those measurements have to be precise because a NIF shot is going to cost a million bucks.”
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> Steve also addresses the scientific quandary which is presented by using a synchrotron to perform calibrations which cannot be performed any other way. He states, “In the main, Livermore's requirements here aren't scientific per se. We're not doing science on the beamlines, but we're making calibration measurements on components and the results of those measurements are critical to science that we do on these platforms. So, any time you read a paper that says 'radiation temperature' and 'hohlraum' that's coming out of Livermore or Los Alamos or LLE they're relying on detectors that are calibrated using this facility. So depending on how you want to do the tally, these are generating tens to hundreds of papers, scientific papers as a result of this work.” In fact, there are numerous examples of scientific papers which make use of radiometric calibration from NSLS (for example PRL 95, 215004 (2005); PRL 94, 065004 (2005); PRL 88, 215004 (2002)). Tom adds that it is important to recognize that it is “..not basic science being performed here but producing data that's necessary to enable good basic science being performed at other facilities.”

Astronomy and Solar Physics
Radiometric satellite-based x-ray instruments are used in astronomy, atmospheric and space weather, under the auspices of NASA, NOAA, and NRL and also require synchrotron-based radiometric and metrological characterization. Development of optics and detectors for solar x-ray spectroscopy requires a dedicated facility which does not exist elsewhere. Currently related metrology/radiometry is occurring at NSLS beamline X24c.

John Seely of NRL briefly described some of the characterization typically performed for space-bound instrumentation. There are in particular needs for EUV and X-ray sensors and imaging systems to be absolutely calibrated for space applications. End-to-end instrument calibration is also an important requirement of those programs.

NASA-funded soft x-ray imaging programs such as Stardust Cosmochemistry, Stardust Organic Chemistry, and Exobiology are interested in proving coherence-preserving optics in order to reach 2-4 nm spatial resolution. Development of detectors and spectral purity beamlines is important for this soft x-ray imaging application.

National Security and Defense

DOE-NNSA and the Nevada Test Site take stewardship of the national nuclear stockpile and maintain weapons test readiness. This readiness takes the form of maintaining functional and calibrated x-ray diagnostics instrumentation. In addition, validation of models for high energy density physics in the ICF sources reduces the need for nuclear tests. The GPS satellite program includes the NUDET x-ray detector suite, capable of quantitatively detecting nuclear weapons tests globally. This program is presently supported by radiometric calibration at beamlines X8a and U3c. Some aspects of the national security need for x-ray calibrations and metrology may not be made public.

Lithography

VUV, EUV, and XUV lithography continues to evolve internationally, and requires extensive characterization at synchrotrons worldwide. Domestically, performance of multilayer EUV optics and dosimetric detectors is being evaluated using ALS, SURF-III and NSLS.

Fundamental Science: Materials Physics and X-ray Optics

Measurement of x-ray optical constants for materials is an ongoing effort by many groups. Measurement of optical properties is key to research and development of optics and detectors. This is presently part of the research effort supported by NSLS beamline X24c.

Beamline Methods and Instrumentation

At-wavelength metrology involves quantitative characterization of mirrors, gratings, multilayers and other elements. These are used, for example, in high-temperature plasma diagnostics, astrophysics, national security, and lithography. These measurements rely on known and controlled polarization. For metrology of highest-performing optics (e.g. mirrors) spatial and spectral coherence of the probe beam is important.

Radiometric characterization of detectors often relies on photoelectric absorption and therefore typically has no specific or strong requirement for beam polarization. However, spatial coherence will be helpful in establishing uniform parallel beams of large size (10 mm or so) which are important for calibration of novel detectors such as diamond photoconductors.

The most important characteristics for these measurements include:

High spectral purity (negligible "out-of-band" light). The spectral purity of the monochromatic beam is a critical feature for radiometry and metrology. The maximum harmonic and stray light power should be less than 1%, but a value as low as 0.1% would be ideal if possible. This is expected to be achieved using harmonic rejection mirror(s) and high quality slits at various point along the beamline.

"Sufficient" monochromatic beam power (flux) to stimulate the detector response over the background / noise level. Flux / optical power: most estimates are 1 GHz / 10 nW minimum. Note: acceptance angle is important, as number of photons collected is proportional to both flux and acceptance. This is an important consideration for comparing output of NSLS-II with NSLS or other domestic synchrotrons. NSLS-II soft bend monochromatic beam power is not expected to be improved with respect to existing VUV bend magnets. The 3PW design was stated as having a fixed 2 mrad acceptance with soft bends possible of delivering up to 5 mrad. ID beamlines are expected to deliver 2 mrad or less but have higher brightness so that acceptance angle in not a limiting factor.

Wide range of photon energies (e.g. 5-150 keV). The meeting identified needs from the visible and IR through 200 keV. To cover 5 eV – 200 keV, natural breakpoints might exist at ~2 keV (transition from grating to Bragg mono, and/or from soft bend to 3PW), and ~ 20 keV (transition from 3PW to wiggler setup). Some users have mentioned a need for lower energies, extending through the visible and IR to 2 μm, as important for basic optical characterization. This would give us "full spectrum metrology" status, unique in the world. Existing soft x-ray beamlines U3c and X24c operate up to ~ 1 keV; X8a operates up to 6 keV, X15a operates up to ~ 25 keV. Currently, access to higher energies is considered via NSLS X17b1. Undoubtedly, this range is accessible with no fewer than 2 beamlines.

Polarization. This is important for metrology of mirrors, gratings and materials optics calibration. In some cases, circular polarization might be ideal, since it delivers the "average" response expected from unpolarized light (useful for calibration under those conditions, e.g. astronomy, solar physics, etc.). Linear polarization is useful, especially if it can be made switchable. Polarization is not important for photoelectric-based detectors and filters of isotropic or amorphous materials under normal incidence.

Probe size. Typical needs range from a few μm to a few mm. Currently beamlines take 0.5-2 mm typical. 10 μm for detailed metrology work may be sufficiently small, but more analysis is needed. Micro beams imply stable micro positioning system with 4-6 axes required. For radiometry several participants indicated interested in even larger, uniform beams up to 10 mm or more, as possible. This would be a unique feature globally if achieved.

Coherence. High degrees of lateral coherence may be important for some metrological applications, but not for all. Mostly this is expected to be important for at-wavelength testing of brightness-preserving optics; however, this feature needs to be ***quantified***.

Energy resolution. This is not a big driver for most work, but important for quantitative results near material edges, and determination of optical parameters. Also, this feature may be critical for at-wavelength metrology as it is coupled to coherence. It has been suggested that 0.2-0.01% resolution should be sufficient for most applications but this needs further analysis and ***quantification***.

Beamline length. For x-ray optics metrology it has been suggested that beamlines may need to be as long as 100-120 meters. This needs further analysis and ***quantification***.

Special source features:
- "Calculable" BM **white light** is highly desirable for radiometric characterization of complete instruments such as spectrometers. This is also useful for metrology. This needs further ***quantification*** but in general if the BM spectrum can be predicted to within <1% over a 0.1% bandpass, that would be useful for such applications.
- At some times, **special timing / fill modes** of the synchrotron beam would be useful (to measure time response of detectors, use of SR as "standard candle" etc.)

Setups (endstations, or beamline configurations) discussed in the meeting (this is not an exhaustive list):
- Reflectivity and scattering of optical elements (θ,2θ setup)
- Tuning and characterization of bendable optics
- Testing and characterization of high-resolution gratings or other monochromator elements/ subsystems
- Phase retrieval, x-ray interferometry
- Detectors may include photodiodes, ion chambers, solid state detectors, high-res CCD with large FOV, etc. (most are available already)
- Software: several groups using labview, would like to continue if possible
- R&D work to be considered:
- x-ray wavefront sensor
- x-ray profilometry instrumentation
- focusing K-B test station with nanopositioning stages
- large instruments to be loaded to the end chamber, up to 1 meter

The Path Forward

The most important next step for this community is to find highly visible scientists and program representatives and increase their direct involvement in the development of radiometry and metrology beamlines at NSLS-II. The scientific justifications exist, but the politics are lacking. One strategy to remedy this is to solicit the collaboration of leaders at similar calibration facilities such as those operated by DOE, NIST, and NASA. These team members can help educate their user base and seek representatives of the relevant field(s) who can participate in the development of NSLS-II beamlines. Existing NSLS users can also bring their management and lead scientists to participate in the next meetings.

It is encouraging that **NIST** sees NSLS-II as an opportunity to extend its existing radiometry and metrology capabilities. This institution has a well-established reputation and mission which evolves with its own user base. Presently, the calibration capabilities of NIST are limited to the visible, UV and VUV range, which leaves an opportunity for work on EUV and x-ray optics and detectors which can be exploited during this formative time.

> Rob Vest is NIST's point of contact for VUV radiometry and metrology at SURF-III. He is very interested in expanding NIST radiometric capabilities to the x-ray range, as he is currently serving mainly space science and lithography in the VUV. Rob has stated in this meeting "our goal is ... to expand our existing calibration capability into the x-rays with sub-percent uncertainties realize the U.S. national scale for detector responsivity." He notes that "..NIST has historically been much more interested in spectroscopy and in the energy calibration of detectors than they have been in the radiometric calibration. So, we're very good at telling you what energy the photons are but we're not so good at telling you how many of them there are. And that's what I'd like to do, is expand our how many photons, our power measurement, into the x-ray regime." Rob has extensive experience and similar perspective to current NSLS radiometry / metrology scientists. He has laid out a three-pronged approach to reaching his stated goal: 1. cryogenic radiometer as an absolute primary standard, 2. 3PW source to reach 20 keV, 3. silicon photodiodes as transfer standards.

NIST's involvement is welcome, and collaborations continue.

Other key players include:

- Tom Tierney (LANL), Steve Vernon (LLNL), Ken Moy (ICF/**NNSA** x-ray diagnostics representatives for LANL, LLNL, SNL/NSTec)
- John Seely (**NRL** beamline representative with connections to **NASA**, **NOAA** and several astronomy related science programs)
- Peter Takacs (BNL) Valeriy Yashchuk (LBNL), Lahsen Assoufid (ANL) as representatives of the **DOE-BES** synchrotron lab-based metrology community
- **NSLS** beamline and instrumentation management may play a role in defining the need for beamline component metrology and radiometry, and may offer guidance to the community and NSLS-II program regarding

strategy and support for beamline component testing activities. The importance of such beamlines could potentially be considered with respect to stated DOE-BES synchrotron mission goals (see http://www.sc.doe.gov/bes/synchrotron_techniques/spectroscopy04.htm)

Questions from the community arose about beamline access and transitioning of beamline components and scientific programs from NSLS.

Access. Can proposals be granted large chunks of beam time? Currently NNSA programs take ~120 days per year on each of U3c, X8a and needs will roughly triple by 2009. Can this need be met? Also, can NNSA maintain “rapid access”-like capability? (Occasionally calibration may be needed with only 1-2 weeks' notice.) Most groups represented at this meeting indicated a need for 20-60% of the year's beam time, which suggests that 2-3 beamlines as described could be fully occupied or oversubscribed by the known user base, additional beamlines might be needed, and core “PU” allocation of 20% or less is not sufficient for most groups. It was mentioned that NNSA and/or other groups may be forced with a “resource-driven” decision to scale down synchrotron efforts in light of perceived reduced return on investment at NSLS-II compared with existing NSLS operations mode.

Tom Tierney (LANL) pointed out that being involved with NIF or ” ... other large-scale facilities and having a SAC assign a schedule to calibrations may not be integral or commensurate with the schedules that we have to keep for our programs ..” He points out that the end user must make the strong argument that “we actually need dedicated beamlines that we have more control over the scheduling of is very important”. On the other hand, he sees the transition to NSLS-II as an opportunity. Building beamlines and organization from scratch might give us ability to run more efficiently, so they need to be designed to provide more flexibility. For example, underground testing was expanded to laser facilities, and nonproliferation detection, many of other developments; he states "having a design be a flexible facility is going to give us a more facility that we can have to offer. It's the correct way to go."

Moving beamlines. Existing groups (x24c, x8a, u3c) might like to save money yet stay involved by moving parts of NSLS beamlines to NSLS-II. What is the feasibility of this?

Mature and sophisticated user groups are currently served by beamlines X24c, U3c, and X8a of NSLS. For these users, the NSLS-II project creates a stumbling block to the continued successful efforts of those communities. Large expenses in the efforts to maintain similar capabilities are difficult to justify, so beamline moves or new construction are expected to be bundled with upgrades to existing beamlines. Some guidance from NSLS and/or NSLS-II is needed to shape these plans for maximum success at the new light source. For example, NRL management is “interested in discussing” moving (most of) beamline X24c, and that PRT feels it is possible to move to a BM at NSLS-II mainly by upgrading first two mirrors. Some engagement is desired by these groups from the NSLS and NSLS-II management, to explore the feasibility of these kinds of options.

Several important deliverables must come from the next meeting:

- Identify the widely-published and highly visible scientists who can stand up and speak for the importance of radiometry / metrology beamlines at NSLS-II.
- Quantify the community's needs for beam coherence
- Develop "straw-man" NSLS-II beamline(s) designs which meet the community's present and future needs

Support by NSLS or NSLS-II program of the community-forming process, including planning and coordination of such meetings is welcome.